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Seeing through the 'Science Eyes' of the ExoMars Rover

Helen C. Miles, Matthew D. Gunn, Andrew J. Coates

Abstract— The ExoMars rover, due to launch in mid 2020, will travel to Mars in search of signs of past or present habitability. The rover will carry the Panoramic Camera, PanCam, a scientific camera system designed to provide crucial remote sensing capabilities as mission scientists search for targets of interest. In preparation for the mission operations, the visual output of PanCam has been simulated and modeled with a 3D rendering system, allowing the team to investigate the capabilities of the camera system and providing insight into how it may be calibrated and used for engineering tasks during the surface mission.

Index Terms— Case Studies in Scientific Applications, Computer Graphics, Graphics packages, Image Generation, Space

1 INTRODUCTION

IN early 2021, the European Space Agency (ESA)/Roscosmos ExoMars rover *Rosalind Franklin* (Fig. 1) will land on the surface of Mars [1] to search for signs of life, past or present. In order to do this, the rover will drill into the ground to retrieve samples protected from solar radiation in the subsurface. The rover's imaging capabilities will come from four camera systems: two scientific camera systems – the Panoramic Camera *PanCam* [2] (shown in Fig. 1) and Close-UP Imager *CLUPI* [3]; and two engineering camera systems – the Navigation Cameras *NavCam* and Localisation Cameras *LocCam* [4], these four systems comprising eight individual cameras in all. Understanding what the cameras will see is vital to interpretation of the images, both in a scientific and an engineering context [5].

Mission preparations include planning how the camera systems will be used to make observations, which requires an understanding of what the camera systems can see. Rover engineers and drivers will use images to plan routes and check the condition of rover hardware, while instrument science team members will use the images to obtain scientific observations and measurements. An additional consideration is the constraints on the power, time and data bandwidth available to the rover, and a host of potential operations to perform. Each sol (Martian day), there will be budgets for power, data, and time, which must be shared between instrument teams and the rover engineers.

During early development, no complete rover is available for imaging tests and schedule constraints prevent extensive testing on the assembled rover. In order to produce images of the rover from the perspective of PanCam, we have created a simulation using a 3D rendering system that can produce representative images using physically realistic mechanical and optical constraints. Images created using the simulation provide insight into the capabilities of the camera system to inform planning and usage for a variety of activities during the surface mission.

2 OVERVIEW OF THE EXOMARS MISSION

ExoMars is a two-part mission: the first part, Trace Gas Orbiter, was launched in 2016 and achieved stable orbit

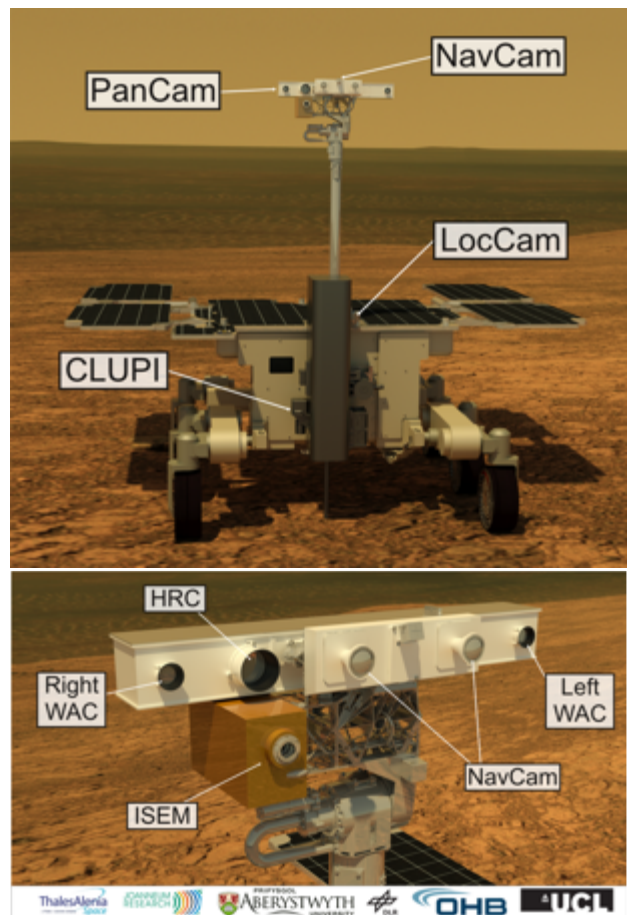


Fig. 1. Visualizations of the ESA/Roscosmos ExoMars mission's Rosalind Franklin rover (above) and PanCam (below) generated from the Computer Aided Design model of the rover in use by the engineering and science teams during the development of the rover. PanCam is located at the top of the mast.

around Mars in 2018; the second part of the mission involves the Rosalind Franklin rover and Kazachok lander platform, scheduled to launch in 2020. Trace Gas Orbiter carries instruments to inspect the Martian atmosphere and will act as the relay satellite for information transmitted between Earth and the rover and lander on Mars.

The rover carries the Pasteur payload, a suite of instruments designed to search for evidence of life [1]. A drill on

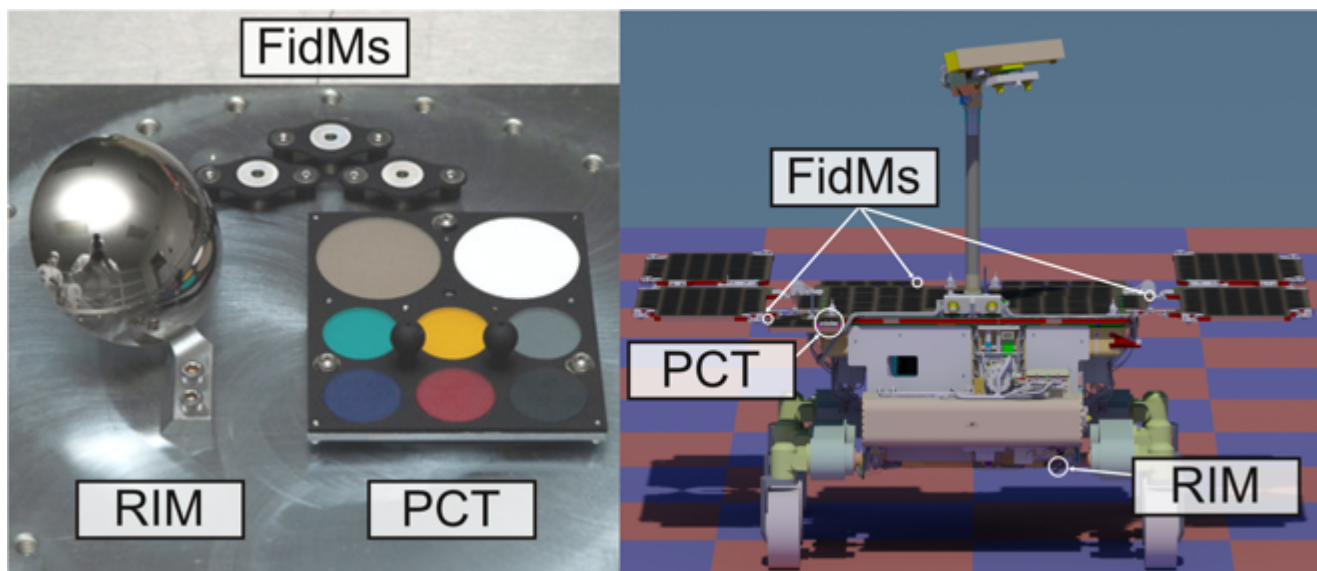


Fig. 2. The PanCam small items – the Rover Inspection Mirror, three Fiducial Markers, and the PanCam and ISEM Calibration Target – and their location on the rover. On the left, a photograph of the real PanCam small items taking during hardware testing (image credit: M. de la Nougerede, UCL/MSSL 2019); on the right, a rendering of the rover ‘looking downwards’ with annotated locations of PanCam and the small items.

the front of the rover (the rotatable box on the front of the rover which is shown in the active drilling position in Fig. 1, and the stowed position in Fig. 2) will collect samples from up to 2 m below the surface and will deposit them in a Sample Drawer on the front of the rover. Inside the rover the Analytical Laboratory will receive and process the sample. The CLUPI camera system is fixed on the outside of the drill box, available to take detailed, high resolution images of the Martian surface [3].

3 THE PANCAM INSTRUMENT

The Panoramic Camera, PanCam, is the primary remote sensing camera system for the ExoMars rover [2]. PanCam contains three individual cameras: two Wide-Angle Cameras (WACs) and the High-Resolution Camera (HRC).

The WACs have a 38.3° field of view and are located 50 cm apart in an enclosure – the Optical Bench – with 2.8° toe-in, providing a wide stereo baseline used to generate 3D terrain mapping data [6], [7]. Each of the WACs is comprised of a one-megapixel (1024×1024 pixel) monochrome CMOS sensor with a fixed focus lens and filter wheel containing 11 filters. Three of the filters in each wheel enable the WACs to acquire colour images (RGB) and are the only identical filters between the two cameras. The remaining filters include solar and narrow band “geology” filters selected to enable remote sensing of mineralogy [8].

HRC has a narrow 4.88° field of view with focus variable from 1 m– ∞ . The camera is folded and housed between the two WACs within the Optical Bench. HRC uses the Bayer colour variant of the one-megapixel CMOS sensor used in the WACs. For targets at a distance of 2 m, each pixel will represent approximately 0.17 mm, while for targets at a distance of 1 km, each pixel will represent approximately 8.5 cm.

PanCam is situated at the top of a mast at the front of the rover, 2 m above the surface. As can be seen in Fig. 1 and Fig. 2, PanCam shares the masthead with NavCam

and the Infrared Spectrometer for ExoMars (ISEM) [9]. A Pan-Tilt Unit (PTU) allows the entire masthead (holding PanCam, ISEM and NavCam) to be tilted up/down $\pm 90^\circ$, and panned left/right $\pm 180^\circ$ from the forward-facing ‘home’ position (the position shown in Fig. 1), enabling capture of a complete sphere. In Fig. 2 the PTU has been panned left by 73° and tilted forward by 44° , allowing PanCam to ‘look’ down towards the front left wheel of the rover.

3.1 The PanCam “Small Items”

To assist in surface operations, PanCam has additional items of hardware, shown in Fig. 2: the PanCam and ISEM Calibration Target (PCT), Rover Inspection Mirror (RIM), and Fiducial Markers (FidMs) [2]. Collectively they are known as the PanCam “small items”.

The PCT allows *in situ* radiometric calibration of PanCam and ISEM. The PCT is manufactured from aluminium with stained glass and ceramic colour patches, which will provide UV-stable reflectance standards, allowing for the generation of calibrated data products. The six smaller glass patches will be used only by PanCam, while the two larger patches will be used by both PanCam and ISEM. Two shadow posts sit between the two rows of smaller patches, enabling the measurement of indirect (skylight) illumination in addition to direct sunlight. Based on the anticipated usage of the PCT, it is likely to be one of the objects most photographed by PanCam.

The RIM is a convex spherical mirror made from nickel-plated polished aluminium, mounted low on the front of the rover. The position and shape of the mirror allow HRC to see reflected views of underneath the rover, underneath the drill box during a drilling operation, and the spoil heap created by the drilling operation.

The FidMs are raised circular markers machined from aluminium and painted black with an exposed circle with a hole at the centre. Placed at three locations across the top deck of the rover, the FidMs provide reference points for *in*

situ geometric calibration. Comparing *in situ* images of the FidMs with pre-flight calibration data will enable engineers to verify that the mast supporting PanCam has been successfully deployed from the stowed position and verify the geometric calibration of PanCam and NavCam.

4 THE VISUAL OUTPUT OF PANCAM

The images captured using PanCam will either be images of the rover itself, or images of the surrounding environment. Four points form the motivation for understanding the visual output of PanCam: understanding what PanCam will see; understanding how PanCam will work; planning operations; and explaining the mission to the general public. The Rosalind Franklin rover will be the first robotic rover platform sent to Mars by ESA, and so there is limited experience of practical rover operations within the European and UK planetary science community. NASA have now successfully operated four rovers on Mars, allowing us to gain some insight from their experiences.

4.1 Understanding What PanCam Will See

What will PanCam be able to see from the top of the rover mast when fully deployed? What will be within the ranges provided by the PTU? What is within the field of view of the individual cameras? Despite the PTU allowing PanCam to rotate in a complete sphere, the fixed relative positions of the cameras on the masthead restricts the views achievable by each individual camera.

Understanding how any remote robotic platform will see the surrounding environment is a complex problem for operators to envisage; even with camera systems which can be thought of as ‘eyes’ the constraints of the rover must be taken into account, and images of the 3D world are returned by the rover as 2D images. Vertesi [10] reports extensively on the visualization and embodiment methods used by scientists and engineers working with NASA’s Mars Exploration Rover (MER) mission, observing that many of them used physical actions such as positioning their bodies to approximate the pose of the rover to help them understand where to point their panoramic camera instrument to capture a target in more detail: “When working with the rover, I am a rover. I am a pancam.”

Although some imaging tests are carried out with the assembled rover, schedule and engineering constraints prevent imaging of all of the rover with its onboard camera systems. Until deployment on Mars, it will only be possible to collect representative images using prototype rover chassis which are built to have the capabilities of the real rover, and not the visual appearance.

4.2 Understanding How PanCam Will Work

What visuals will be afforded by the electronics and optics within the camera systems? What will the HRC focus mechanism enable us to see? How will the images taken using the different WAC filters look?

For *in situ* calibration of PanCam, the PCT will provide ground truth reflectance data used to convert the images into calibrated data products – actual measures of the interaction between the light source and the objects in the scene as opposed to pixel colours. Vertesi [10] describes

LIST OF ABBREVIATIONS

AUIPE	Aberystwyth University PanCam Emulator
AUPS	Aberystwyth University PanCam Simulator
ALD	Analytical Laboratory Drawer
CLUPI	Close-UP Imager
CCT	CLUPI Calibration Target
FidM	Fiducial Marker
HRC	High-Resolution Camera
ISEM	Infrared Spectrometer for ExoMars
MLI	Multi-Layer Insulation
PTU	Pan-Tilt Unit
PCT	PanCam and ISEM Calibration Target
RIM	Rover Inspection Mirror
WAC	Wide-Angle Camera

how scientists performing *in situ* calibration of the MER panoramic camera “relied on their knowledge of the camera’s electronics to know whether the instrument was working properly”. This is partly related to whether people understand how the cameras function electronically and optically, but is also partly to do with our expectation of how they will work – i.e. if we have an idea of what they should see using different configurations then we can use that information to our advantage. A clear understanding of the capabilities of the camera systems will be very beneficial for operations, and may be a capability developed by those working on the mission as the panoramic camera operators on MER developed “a sensibility to what the rover might see, think, or feel related to specific activities that must be planned” [10].

4.3 Planning Operations

Mission operations and measurement sequences must be considered long before the rover reaches Mars. Some routine activities are pre-programmed to minimize telemetry overheads and so we must know how the activity should be carried out. An example of a routine activity is imaging the PCT to allow radiometric calibration. This may occur as much as once per Sol during routine driving and several times in a Sol during detailed science imaging operations. Some activities may occur infrequently such as using the CLUPI Calibration Target (CCT) alongside the PCT to provide additional calibration data for PanCam. Can PanCam clearly view the CCT? If so, how many pixels will patches provide for a statistical analysis? In what scenarios could using the CCT be useful?

4.4 Public Engagement

Public engagement is vital during space exploration, capturing the imagination of the public and inspiring future scientists. NASA have found great success in their Mars Science Laboratory mission with the *Curiosity* rover taking self-portraits on Mars using the MAHLI instrument on the end of a robotic arm [13]. While the ExoMars rover does not have a robotic arm, it will be possible for the images of the RIM to be used in a similar way, showing the rover working on Mars. The potential for public engagement with these images should not be underestimated – they provide a tantalizing glimpse into the world of the rover.

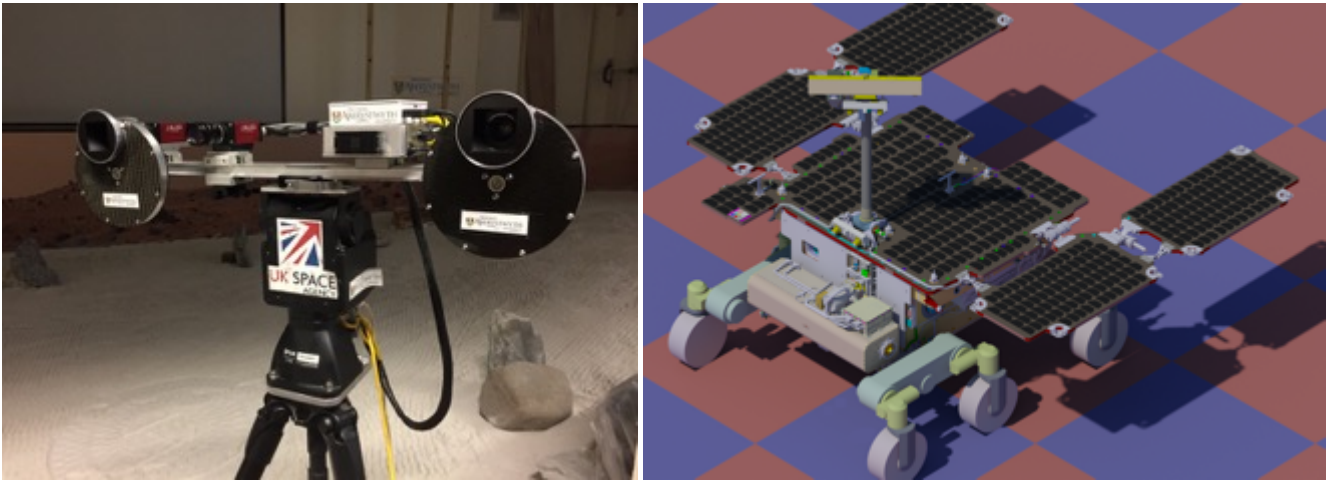


Fig. 3. An emulator and simulator pair used together to explore possible uses of PanCam. On the left, the Aberystwyth University PanCam Emulator (AUPE) provides representative imaging capabilities and has been used in many field campaigns by geologists and planetary scientists to capture data for analysis and developing image processing procedures. On the right, the Aberystwyth University PanCam Simulator (AUPS) provides data which AUPE cannot – images of the rover body from the perspective of the camera systems (e.g. Fig. 4).

5 SIMULATION (AUPS) AND EMULATION (AUPE)

In order to understand the visual output of PanCam for both subjects, PanCam has been simulated and emulated by the two systems described in this section (see Fig. 3).

Simulation and emulation provide contrasting but complementary results which will enable the team to prepare for the mission: while emulation produces representative data output from the camera system in terms of the optical properties and the result of using filters, simulation can provide images with additional contextual information.

Emulation of the images produced by PanCam has been crucial to the development of techniques to exploit the images of the environment for scientific data. An emulator for PanCam which has been involved in several major field campaigns is AUPE (the Aberystwyth University PanCam Emulator [11], Fig. 3) which provides emulation of the pan-tilt movement, HRC, and WACs with filters. Typical usage of AUPE involves visiting a Mars analogue site and capturing an image sequence. The images are processed into data products using the interactive 3D visualization and image analysis tool PRo3D [6], [7] and multispectral

analysis tool ExoSpec [12]. While AUPE offers insight into the scientific data produced using PanCam, it is not possible to emulate accurate images of the rover without building a complete and accurate physical model.

In order to produce images of the rover body from the perspective of PanCam, a simulation of PanCam has been developed using industry-standard computer graphics software (see Figs. 3-10): the Aberystwyth University PanCam Simulator (AUPS). Fully specified cameras (including field of view, focal distance, sensor size and depth of field) simulate each of the two WACs and HRC in order to generate visually correct output from each of the cameras. The rover's PTU can be rotated with kinematic motion constraints applied to the camera transforms. Once the camera target has been acquired by manipulating the PTU, images can be rendered to the correct resolution of 1024×1024 .

Images rendered using AUPS provide insight into the visibility of rover hardware, demonstrating how the real images could be used for a variety of activities during the surface mission. For the simulated images presented here, the rover is situated at the centre of a 20 m^2 flat plane with a uniform 20×20 grid (resulting in 1 m^2 grid squares).



Fig. 4. A set of three images produced by AUPS where HRC has been aimed directly at the centre of the PCT, producing the accompanying Left and Right WAC images. In this configuration, the PCT patches are almost fully visible to HRC, the PCT is centred in the right WAC, but is very close to the edge of the left WAC.

6 SIMULATED VISUAL OUTPUT

AUPS has been utilised for a variety of tasks during hardware development, field campaigns, instrument calibration, and public engagement. Here we present six case studies of imaging tasks for items on the rover chassis.

6.1 PanCam Calibration Target (PCT)

In order to radiometrically and colorimetrically calibrate PanCam *in situ*, the PCT must be imaged by whichever cameras are required to take photographs. Images must be captured with each filter that is being used for science imaging to determine the incident solar illumination. In WAC images the PCT will only account for a small region and so sub-frames can be returned to minimise the data volume. If the PCT can be imaged with all three cameras simultaneously (as shown in Fig. 4), the effect on the time and power budget, and the wear on the PTU will be minimised.

For calibration, the greater the number pixels available to determine the reflectance for each patch, the more confidence we can have in the result statistically. For the three images in Fig. 4, the average number of pixels per patch in has been recorded in Table 1. Although patches are of two sizes, the number of pixels varies per patch, particularly when they are obscured by the shadow posts or are partially cut off at the edge of the image. The number of pixels in the WAC images are approximately 1% of those in HRC.

If the procedure of capturing images of the PCT is defined as a specific pan-tilt angle set, images from AUPS can be used to define regions of interest for the auto-exposure and sub-framing the images before downlink, or automatically masking them after downlink.



Fig. 5. Images of the RIM, comparing a simulated image produced using AUPS (left) and an image captured by AUPE during a field trial (center) demonstrates the visual fidelity of the images. Right, a closer view of the RIM image, cropped from the original image shown on the left. PanCam is visible at the top of the mirror looking down.

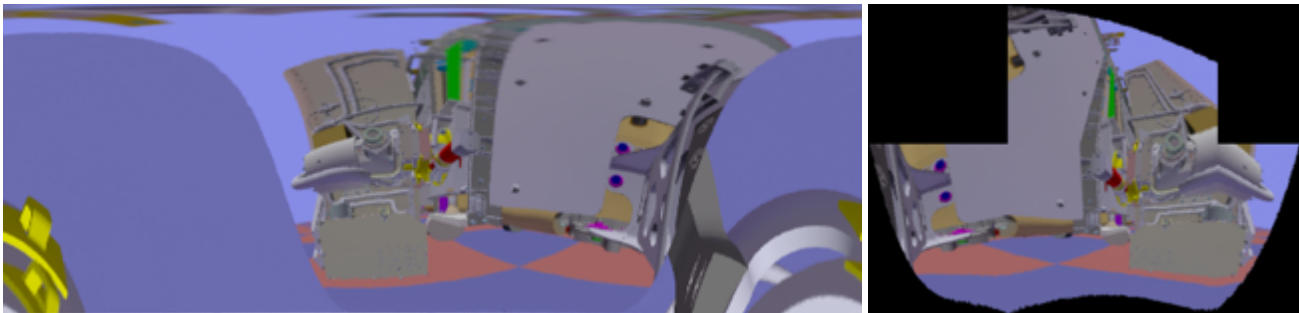


Fig. 6. The simulated image of the RIM has been dewarped, demonstrating the resulting distortion and low resolution. On the left, the initial image dewarping turns the image into a panorama; on the right, the panorama reprojecting the panorama as a cubemap and cropped.

TABLE 1
PIXELS PER PCT AND CCT PATCH FOR EACH CAMERA

Target Patch	Number of Pixels		
	LWAC	HRC	RWAC
PCT 18 mm	380 ± 3.0%	36380 ± 10.8%	390 ± 3.1%
PCT 30 mm	1090 ± 3.4%	111130 ± 3.0%	1150 ± 1.6%
CCT 6 mm	30 ± 2.4%	2880 ± 0.3%	30 ± 5.2%

Selections of pixels made from the three images shown in Fig. 4 and Fig. 7. The average number of pixels and standard deviation (%) of each type of patch are recorded. The large standard deviation in the PCT patches is due to patches being cut off at the edge of the image or being obscured by the shadow posts.

6.2 Rover Inspection Mirror (RIM)

In Fig. 5, a view of the RIM produced using AUPS is compared with an image captured by AUPE during a field trial. During the field trial the rover chassis was approximately 90% scale and the RIM was fitted to the rover by eye, resulting in slightly different geometry. Despite these differences, it is possible to verify the quality and visual fidelity of the AUPS image based on this real-world equivalent.

The images of the RIM are returned with extreme barrel distortion from the mirror; the image must be ‘unwrapped’ from the surface of the mirror to correct the distortion. This is achieved through a dewarping process, the results of which can be seen in Fig. 6. Looking directly into the ‘eyes’



Fig. 7. The three FidMs as seen by HRC in their different locations on the rover deck. The FidMs will be used to geometrically calibrate PanCam once the mast has deployed, ensuring it has unfolded correctly.

of the rover allows the viewer to feel a connection with the rover and its journey. However, the process of dewarping the RIM image into a panorama causes severe stretching of the image around the pixels reflecting PanCam. Reprojecting the panorama into a cubemap allows for the stretching of the ground portion of the images without deforming the portion of the image containing PanCam.

A further issue with the HRC images of the mirror is the resulting resolution: the original image is only 1024×1024 pixels, once the image has been processed into a panorama the resolution is reduced to 835×266 pixels while the cropped cubemap is 427×307 pixels.

6.3 Fiducial Markers (FidMs)

The FidMs enable geometric calibration of PanCam and will be imaged using HRC to ensure that the mast has deployed correctly after unfolding from the stowed position. Fig. 7 shows each of the three FidMs as they will be seen by HRC on their positions across the rover deck. Two of the FidMs are located on the sides of the rover deck, with the third (the rightmost image in Fig. 7) placed at the back of the rover. When the solar array is folded to fit on top of the deck during transit, the third marker will be hidden by the solar array hinge; an extension has been manufactured to allow its location to be determined during calibration when the arrays are stowed. This is an example of a scenario which was difficult for designers to foresee without access to the visual output of the camera system, as the solar array, FidMs, geometric calibration process, and PanCam hardware are being developed by different groups within the rover and PanCam teams.

6.4 CLUPI Calibration Target (CCT)

Although the CLUPI Calibration Target (CCT) is primarily

for the use of the CLUPI camera system [3], it will be possible for PanCam to use the CCT for additional calibration measurements and cross-calibration between the two instruments. Seven of the nine patches of glass in the CCT are the same specification and batch as ones from the PCT. Fig. 8 offers views of the CCT when centred in HRC: the patches are clearly visible to HRC; in the left WAC the CCT is visible but occupies a small number of pixels; both the CCT and PCT are visible in the right WAC. Note that the visibility of the CCT is dependent on the drill being rotated to upright from the stowed position, and that this is also the case for the RIM, which is visible opposite the CCT in the left WAC. As with the PCT, the average number of pixels per patch for the three images in Fig. 8 has been recorded in Table 1. The CCT patches are all the same size, but it is smaller and further from PanCam. Again, the number of pixels per patch in the WAC images is approximately 1% of those in the HRC image.

6.5 Analytical Laboratory Drawer (ALD)

When a sample is deposited in the Analytical Laboratory Drawer (ALD) by the drill, it can be viewed by HRC (see Fig. 9) before being retracted into the rover. In the background of the HRC image the CCT is visible, slightly out of focus but providing an opportunity to calibrate the image containing the sample. Both the PCT and CCT are visible to the right WAC, however with the drill in the depositing position the ALD is not at all visible in the left WAC.

Each of the two WACs contain half of the geology filter set; if there was a requirement to image the sample using the left WAC to obtain a complete spectral dataset, it would be necessary to move the drill from the depositing position to a vertical lowered position (shown in Fig. 9). Once a sample from the Martian subsurface has been collected by the drill it will need to be ingested as soon as possible to prevent contamination and degradation by the solar UV. These visualisations will aid planning of sample imaging sequences and highlight the constraints on operations.

6.6 ISEM Multi-Layer Insulation (MLI)

ISEM – the Infrared Spectrometer for ExoMars [9] – is an infrared pencil beam spectrometer mounted below PanCam, coaligned with HRC. In order to survive the cold Martian environment, ISEM is wrapped in Multi-Layer Insulation (MLI) which is made from gold-coated Mylar film.

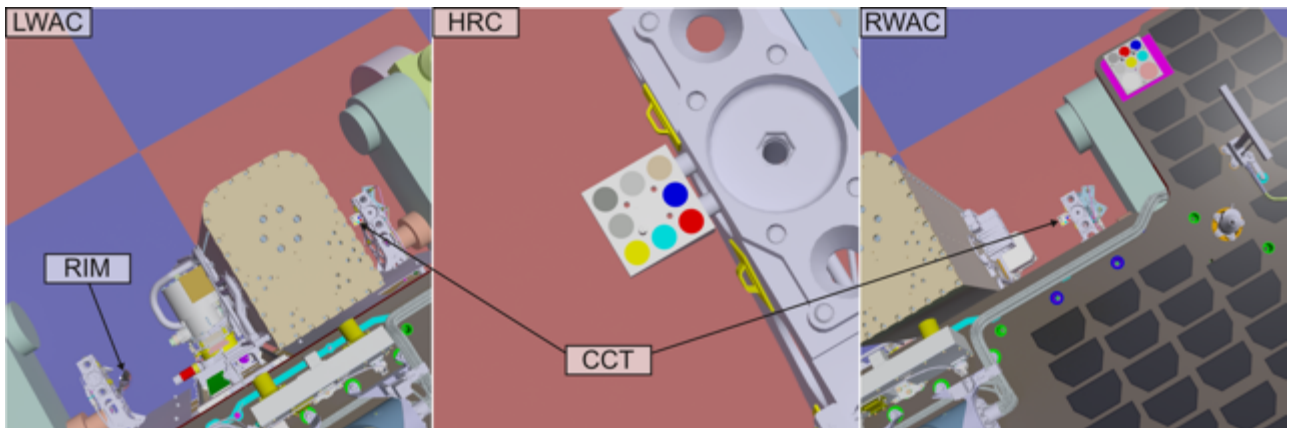


Fig. 8. Views of the CCT, barely visible in the WACs but clear in HRC; the PCT is also visible to the right WAC enabling cross-calibration.

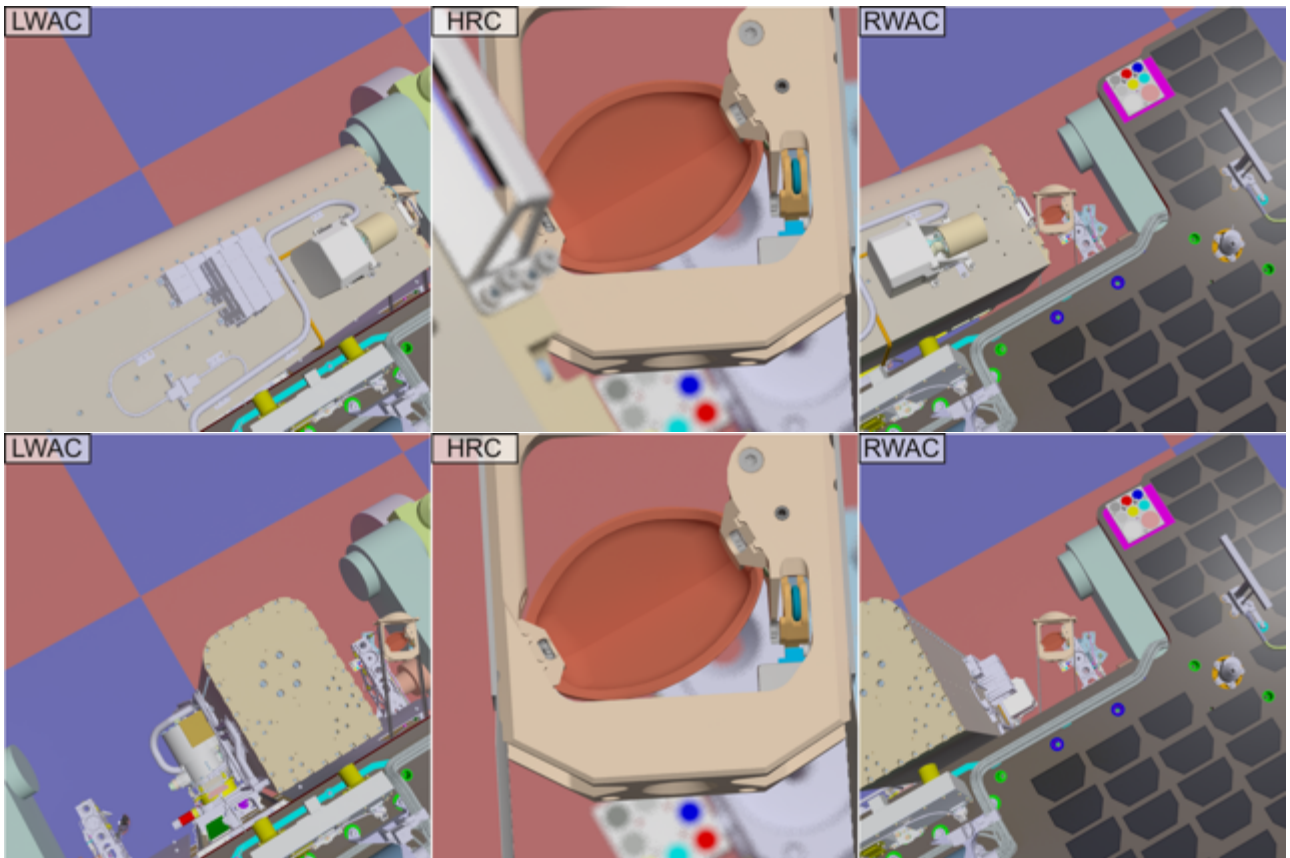


Fig. 9. Views of the ALD drawer when the drill is depositing a sample (top) and when the drill has been lowered (bottom). Note that the sample will not be visible at all in the left WAC when the drill is depositing. With different filters in each WAC and limited time to ingest the sample, this has significant implications for sample imaging. When the drill is lowered the ALD is visible to the left WAC. Note that the CCT is visible behind the ALD in both HRC images, and the PCT is visible in the right WAC images.

ISEM extends beyond the HRC stray light baffle (see Fig. 1) and the MLI is highly reflective, prompting concerns that low sunlight would reflect from the film into HRC's lens, effectively blinding the camera.

AUPS was used to investigate this potential issue by investigating the sun angles over which reflection from the MLI into HRC was likely. This was achieved by artificially widening HRC's field of view in order to see when reflected light began travelling past the baffle (examples shown in Fig. 10). It was found that when the MLI reflected light into the HRC window, the direct sunlight would also reach the window and so the stray light contributed by the MLI is likely to be dominated by that from direct illumination.

7 DISCUSSION

The AUPS simulator and AUPE emulator are highly complementary systems: where AUPS can be used to simulate environments not yet encountered or difficult to replicate, AUPE provides physically representative hardware which can be taken into the field for experimentation and gaining understanding of the data which will be captured by the flight model of PanCam which travels to Mars.

7.1 Understanding What PanCam Will See

The simulations presented are currently captured in 'perfect conditions', lacking many of the complications which will be experienced during the real mission, e.g. complex

light scattering in the dusty atmosphere, however they do provide awareness of what the camera will see. Prior to using AUPS, many of the science team members did not know how the images from PanCam would look, with only images from field trials (many taken by AUPE) to compare to; these images offer some understanding, but the trials have not yet featured a complete, full-scale rover.

To allow mission scientists to analyse the images returned by PanCam with confidence, it is vital to statistically characterise the contents of the image. AUPS is ideally suited to this task because the targets of interest in the images can be manipulated to facilitate characterisation. It is possible for quantitative analysis of the images produced by AUPS, because it facilitates pixel counting and accurate analysis of images through full control of lighting and materials. It provides full control over the scene, allowing investigation of PanCam in any simulation which can be replicated within the AUPS environment.

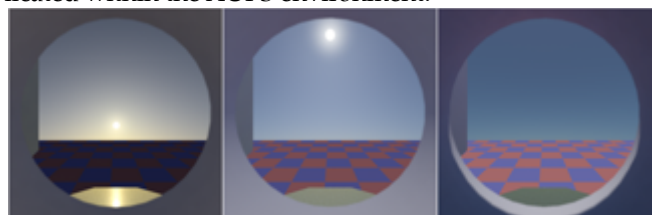


Fig. 10. A selection of the renderings generated to investigate whether the gold coated MLI around ISEM would reflect sunlight into HRC. The field of view of HRC has been artificially widened and the top of ISEM can be seen at the base of the image.

7.2 Understanding How PanCam Will Work

AUPS does not yet simulate views through the different filter wheels, however it has been used to investigate camera optics in other ways. The use of the focus mechanism on HRC has been examined during several small studies, including as part of the planning for pre-flight calibration activities. It has also been used to investigate potential issues arising, for example possible stray light reflected from the insulation around ISEM.

7.3 Planning Operations

In order to capture images of objects with high confidence of measurement quality, the subject should be as close to the centre of the image as possible. The primary on-board targets have been investigated from the perspective of PanCam, finding in multiple situations that the use of AUPS enabled greater understanding of the targets. In some cases, unanticipated modifications may need to be made to procedures, for instance, calibrating both WACs and HRC with the PCT near the centre of the WAC images from a single pan-tilt position is not possible. AUPS has been used to determine the optimal pointing directions as part of planning for rover level calibration activities.

7.4 Public Engagement

AUPS can be used to generate images which can be shown to the public, and videos which explain instrument functionality. Understanding what images will be returned by the rover enables the planning of images for engagement in addition to science and engineering activities, for example, the RIM self-portraits. For the self-portraits of the Curiosity rover the images can be carefully constructed so that the viewer looks straight at the rover as though they were there taking the photograph; the images are not obviously self-portraits. For the Rosalind Franklin rover this will not be possible, but the RIM images offer a comparable way of bringing the viewer into the world of the rover and feel like a personal image taken and sent by a friend.

8 CONCLUSION

In this paper we have demonstrated that science teams working with cameras for space exploration missions can utilise computer graphics to gain a greater understanding of the capabilities of their instruments. We have found that for missions like ExoMars, where power and data allowances mean that each image must be carefully debated, understanding the visual output of the cameras using industry-standard tools has proven extremely valuable.

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REFERENCES

- [1] J.L. Vago, F. Westall, A.J. Coates, R. Jaumann, et al., "Habitability on Early Mars and the Search for Biosignatures with the ExoMars Rover," *Astrobiology*, vol. 17, no. 6-7: pp. 471-510, 2017.
- [2] A.J. Coates, R. Jaumann, A.D. Griffiths, C.E. Leff, et al., "The Pancam Instrument for the ExoMars Rover," *Astrobiology*, vol. 17, no. 6-7: pp. 511-541, 2017.
- [3] J.-L. Josset, F. Westall, B.A. Hofmann, J. Spray, et al., "The Close-Up Imager onboard the ESA ExoMars rover: objectives, description, operations, and science validation activities," *Astrobiology*, vol. 17, no. 6-7, p. 595-611, 2017.
- [4] N. Cristello, V. Pereira, A. Deslauriers, and N. Silva. "Exomars Cameras – an Input to the Rover Autonomous Mobility System". in CIM Montreal. 2015.
- [5] M. Gunn and C. R. Cousins, "Mars surface context cameras past, present, and future," *Earth and Space Science*, vol. 3, no. 4, p. 144-162, 2016.
- [6] G. Paar, R.G. Deen, J.-P. Muller, et al., "Vision and image processing," *Contemporary Planetary Robotics: An Approach Toward Autonomous Systems*, 2016.
- [7] R. Barnes, S. Gupta, C. Traxler, et al., "Geological analysis of Martian rover-derived digital outcrop models using the 3D visualisation tool, planetary robotics 3D viewer-PRo3D." *Earth and Space Science*, 2018.
- [8] C.R. Cousins, M. Gunn, B.J. Prosser, et al., "Selecting the geology filter wavelengths for the ExoMars panoramic camera instrument," *Planetary and Space Science*, vol. 71, no. 1, p. 80-100, 2012.
- [9] O.I. Korabiev, Y. Dobrolensky, N. Evdokimova, A.A. Fedorova, et al., "Infrared Spectrometer for Exomars: A Mast-Mounted Instrument for the Rover," *Astrobiology*, vol. 17, no. 6-7: pp. 542-564, 2017.
- [10] J. Vertesi, "Seeing Like a Rover: How Robots, Teams, and Images Craft Knowledge of Mars". 2015: University of Chicago Press.
- [11] J.K. Harris, C. R. Cousins, M. Gunn, et al. (2015). "Remote detection of past habitability at Mars-analogue hydrothermal alteration terrains using an ExoMars Panoramic Camera emulator." *Icarus* 252: 284-300.
- [12] E.J. Allender, R. Stabbins, M. Gunn, et al., "The ExoMars spectral tool (ExoSpec): an image analysis tool for ExoMars 2020 PanCam imagery," in *Image and Signal Processing for Remote Sensing XXIV*, vol. 10789. International Society for Optics and Photonics, p. 1078901, 2018.
- [13] E. Lakdawalla, "The Design and Engineering of Curiosity: How the Mars Rover Performs Its Job". 2018: Springer.

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